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13. ABSTRACT (Maximum 200 words)  While <i>interband</i> transitions in quantum dots have been extensively investigated for long wavelength (1.3 $\mu\text{m}$ and 1.55 $\mu\text{m}$ ) optical communications, <i>intersubband</i> transitions between the electronic levels formed in the conduction band of the quantum dot have not been widely researched. Since the intersubband energy spacing lies in the mid-infrared (3-20 $\mu\text{m}$ ) range, these transitions can be used for fabricating mid-infrared sources and detectors, which are in great need for applications such as space based infrared imaging, thermal imaging, night vision, thermography for electrical and mechanical fault detection, FTIR spectroscopy and environmental and chemical process monitoring. In this project, intersubband transitions in self-organized In(Ga)As/GaAs quantum dots were investigated and mid-infrared sources and detectors were fabricated. Spontaneous and stimulated emission centered at 13 $\mu\text{m}$ , was observed for the first time. We have also fabricated normal incidence quantum dot detectors ( $\lambda_p \sim 4\mu\text{m}$ ) with very low dark current ( $I_{\text{dark}} = 1.7 \text{ pA}$ for $V_{\text{bias}} = 0.1 \text{ V}$ , $T = 100\text{K}$ ), high detectivity ( $D^* = 3 \times 10^9 \text{ cmHz}^{1/2}/\text{W}$ , $T = 100\text{K}$ ), and peak responsivity, $R_p = 2 \text{ mA/W}$ ( $T = 100\text{K}$ ) with a photoconductive gain, $g = 18$ ( $V_b = 0.3\text{V}$ , $T = 100\text{K}$ ) with the highest operating temperature (150K) for any normal incidence vertical quantum dot detector.			
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**Final Progress Report**

**“ Long-Wavelength Quantum Dot Intersubband Optoelectronic Devices”**

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## Introduction

Mid-infrared (3-25  $\mu\text{m}$ ) semiconductor sources and detectors are essential for thermal imaging, atmospheric communications, chemical spectroscopy, night vision, space based infrared imaging, thermography for electrical and mechanical fault detection and environmental and chemical process monitoring. Currently used MIR sources and detectors are based on low bandgap materials like the lead salts, HgCdTe and antimonides, which are difficult to grow and process. Quantum well infrared photodetectors (QWIPs) and the quantum cascade laser are recently demonstrated devices that rely on intersubband transitions in quantum wells. However, due to the large dark current in QWIPs and the poor radiative efficiency in the quantum cascade lasers, these devices are still limited to operation at cryogenic temperatures.

Quantum dot detectors are expected to demonstrate good performance at elevated temperatures, due to their favorable carrier dynamics. The theoretically obtained dark current in quantum dot detectors is much lower compared to the dark current in QWIPs, primarily due to the large intersubband relaxation time in the dots. The large intersubband relaxation time also ensures the easy achievement of population inversion between the electronic excited states and the ground state in the conduction band of the dot, thus invoking the possibility of obtaining intersubband emission from the dots.

## Statement of Problem Studied

In this project, researchers at the University of Michigan have investigated the possibility of using intersubband transitions in quantum dots to realize mid-infrared sources and detectors ( $\lambda=3\text{-}20\mu\text{m}$ ). The unique carrier dynamics that existed in this quasi-zero dimensional system were also studied.

## Summary of Important Results

In the first part of the work, the growth of self-assembled quantum dots was optimized to obtain high quality dots with narrow photoluminescence linewidths. The carrier dynamics in these dots were measured by performing high frequency electrical impedance measurements on quantum dot lasers. The long relaxation times that were obtained by this measurement were corroborated by differential transmission spectroscopy (DTS) measurements performed in Prof. Ted Norris's group at the Center for Ultrafast Optics. At the University of Michigan, *we have established that carrier relaxation times in these dots are favorable for high-temperature operation of the intersubband devices.* In the final phase of the project, intersubband sources and detectors were designed, grown, fabricated and characterized. *Intersubband spontaneous and stimulated emission was observed for the first time in self assembled quantum dots. Normal incidence InAs/GaAs mid infrared ( $\lambda = 4\mu\text{m}$ ) quantum dot detectors with the highest detectivity ( $D^*=3\times 10^9 \text{ cmHz}^{1/2}/\text{W}$ ,  $T=100\text{K}$ ), lowest dark current ( $I_d= 1.65 \text{ pA}$ ,  $V_b=0.1\text{V}$ ,  $T=100\text{K}$ ) and highest operating temperature ( $T=150\text{K}$ ) were reported.*

The main accomplishments of the project are summarized here:

- **First Observation of Intersubband Spontaneous Emission ( $\lambda=13\mu\text{m}$ ) from Quantum Dots**

Far infrared (FIR) spontaneous emission at 300K and lower temperatures, due to intersubband transitions in self-organized  $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}/\text{GaAs}$  quantum dots, were characterized. Measurements were made with a multi-dot layer near-infrared ( $\sim 1\mu\text{m}$ ) interband laser. The FIR signal, centered at  $12\mu\text{m}$ , was enhanced after the interband transition reached threshold suggesting that the FIR emission is due to intersubband transitions and not due to blackbody heating of the devices.

- **First Demonstration of Stimulated Emission and Intersubband Gain in Quantum Dots**

A plasmon enhanced waveguide was designed, grown and fabricated to confine the long wavelength far infrared ( $\lambda=13\mu\text{m}$ ) mode. Intersubband gain as high as  $250\text{ cm}^{-1}$  was calculated for the intersubband transition in self-organized  $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}/\text{GaAs}$  quantum dots using a two-photon rate equation model. The devices demonstrated intersubband gain and dominant stimulated emission with a distinct threshold behavior, inspite of the very small confinement factor ( $\Gamma=3.7\times 10^{-4}$ ). The FIR emission is predominantly TE polarized in accordance with the results obtained using an 8 band **k.p** model.

- **Demonstration of Normal Incidence Vertical InAs/GaAs Mid-Infrared ( $\lambda=4\mu\text{m}$ ) Quantum Dot Detectors with High Detectivity, Low Dark Current and High Temperature Operation**

Current blocking AlGaAs layers were symmetrically and asymmetrically placed in a 10-layer InAs/GaAs quantum dot detector and the heterostructure was optimized for high temperature performance. The best results were obtained with an asymmetrically placed single  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{GaAs}$  barrier. *Using this design, normal incidence detectors operating between  $3.5\text{--}5\mu\text{m}$  were fabricated with the highest detectivity ( $D^*=3\times 10^9\text{ cmHz}^{1/2}/\text{W}$ ,  $T=100\text{K}$ ), lowest dark current ( $I_d=1.65\text{ pA}$ ,  $V_b=0.1\text{V}$ ,  $T=100\text{K}$ ) and highest operating temperature ( $T=150\text{K}$ ) in vertical quantum dot detectors.*

- **Demonstration of High Temperature Operation of Modulation Doped Lateral InAs/GaAs Quantum Dot Detectors**

Modulation doped lateral InAs/GaAs quantum dot detectors with interdigitated contacts were grown, fabricated and characterized for mid infrared detection at  $T=78\text{K}$  and  $T=100\text{K}$ . Due to the small lateral interdot tunneling, the dark current in these devices was very low and at  $T=100\text{K}$ ,  $I_{\text{dark}}=0.027\text{ nA}$  for  $V_{\text{bias}}=0.5\text{ V}$ . The peak of the spectral response curve was at  $\lambda=5.05\text{ }\mu\text{m}$  with  $\Delta\lambda/\lambda=0.45$ . At  $T=78\text{K}$ , the peak detectivity,  $D^* = 2.4 \times 10^8\text{ cmHz}^{1/2}/\text{W}$ , and peak responsivity,  $R_p=9.9\text{ mA/W}$  with a photoconductive gain,  $g=8.7$  and quantum efficiency equal to 0.25% for  $V_b=-4\text{V}$ . These measurements were done in collaboration with Dr. S. Kennerly at the Army Research Laboratory.

#### **• Narrow Linewidth Quantum Dots for Multi-spectral and Hyperspectral Detectors**

The molecular beam epitaxial growth of self-organized  $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}$  dots on buried  $\text{InGaAlAs/GaAs}$  stressor dots has been characterized by photoluminescence measurements and cross-sectional transmission electron microscopy. The presence of the stressor dots enhances the growth rate and spatial uniformity of the  $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}$  dots. The incorporation of Al in the stressor dots not only provides a strain field, but also enables selective radiative recombination in the active dots. A low photoluminescence linewidth of  $19\text{ meV}$ , almost invariant in the temperature range of  $7\text{-}100\text{K}$  was measured in a heterostructure with an optimal number of stressor and active dot layers.

#### **Technology Transfer/Initiatives**

The group working on far infrared detectors at Rockwell have been interested in our results and some of our samples were sent to them.

#### **Report of Inventions**

None.

#### **Scientific Personnel (Honors/Awards/Degrees Received)**

Pallab Bhattacharya, John Simon Guggenheim Award, 1998.  
Pallab Bhattacharya, IEEE/LEOS Distinguished Lecturer Award, 1998.  
Pallab Bhattacharya, James R. Mellor Endowed Professorship, 1999.  
Jamie Phillips (Graduate Student), Best Student Paper Award, NAMBE, 1999.  
Pallab Bhattacharya, SPIE Technology Achievement Award, 2000.  
Pallab Bhattacharya, IEEE (LEOS) Engineering Achievement Award, 2000.  
Pallab Bhattacharya, Paul Rappaport Award, IEDM 2000.  
Sanjay Krishna (Graduate Student), Best Student Paper Award, NAMBE 2000.  
Sanjay Krishna, PhD degree in Applied Physics, 2001.

## List of Manuscripts:

### A. Manuscripts submitted:

1. "Intersubband Gain and Stimulated Emission in Long Wavelength ( $\lambda = 13\mu\text{m}$ ) Intersubband In(Ga)As/GaAs Quantum Dot Electroluminescent Devices", S. Krishna, P. Bhattacharya, J. Singh, T. Norris, J. Urayama, P.J. McCann, and K. Namjou, Submitted to *Journal of Quantum Devices*, January 18, 2001.
2. "High Detectivity, Normal Incidence, Mid-Infrared ( $\lambda \sim 4\mu\text{m}$ ) InAs/GaAs Quantum Dot Detector Operating at 150K", A. D. Stiff, S. Krishna, P. Bhattacharya, and S. Kennerly, Submitted to *Applied Physics Letters*, April 19, 2001.

### B. Papers published in peer-review journals:

1. "Use of Kubo Formalism to Study Transport Beyond the Born Approximation: Application to Low-Temperature Transport in Si Metal-Oxide-Semiconductor Field-Effect Transistors:", Y. Zhang and J. Singh, *Appl. Phys. Lett.*, **73**, 1577, (1998).
2. "Growth of High Density Self-Organized (In,Ga)As Quantum Dots with Ultranarrow Photoluminescence Linewidths Using Buried In(Ga,Al)As Stressor Dots", S. Krishna, J. Sabarinathan, K. Linder, P. Bhattacharya, B. Lita and R.S. Goldman, *J. Vac. Sci. Technol.*, **B18**, 1502, May/June 2000.
3. "Photoluminescence linewidth of self-organized  $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}/\text{GaAs}$  quantum dots grown on InGaAlAs stressor dots," S. Krishna, K. Linder, and P. Bhattacharya, *Journal of Applied Physics* **86**, 4691, October 15, 1999.
4. "Evidence of Interdot Electronic Tunneling in Vertically Coupled  $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}$  Self-Organized Quantum Dots," J. Urayama, T.B. Norris, B. Kochman, J. Singh and P. Bhattacharya, *Appl. Phys. Lett.*, **76**, 2394, (2000).
5. "Room-temperature long-wavelength ( $\lambda - 13.3\mu$ ) unipolar quantum dot intersubband laser," S. Krishna, P. Bhattacharya, P.J. McCann, and K. Namjou, *Electronics Letters* **36**, 1550, 2000.

### C. Conference presentations

1. "Reduction of Photoluminescence Linewidths in Self-Organized  $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}/\text{GaAs}$  Quantum Dots Grown on InGaAlAs Stressor Dots," S. Krishna, K. Linder, J. Sabarinathan, and P. Bhattacharya, paper presented at the 18<sup>th</sup> North American Conference on Molecular Beam Epitaxy, June 1999.
2. "Optoelectronic Device Applications of Self-Organized In(Ga,Al)As/Ga(Al)As Quantum Dots", P. Bhattacharya, S. Krishna, D. Zhu, J. Phillips, D. Klotzkin, O. Qasaimeh, W.D. Zhou, J. Singh, P. J. McCann, and K. Namjou, paper presented at the Materials Research Society Annual Meeting, San Francisco, April 2000.
3. "Quantum dot carrier dynamics and far-infrared devices", P. Bhattacharya, S. Krishna, J. Phillips, D. Klotzkin, and P. McCann, abstract submitted to SPIE for Photonics, Taiwan, May 2000.
4. "Spontaneous Far Infrared Emission from Self Organized  $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}/\text{GaAs}$  Quantum Dots", S. Krishna, O. Qasaimeh, P. Bhattacharya, P. J. McCann and K. Namjou, *Electronic Materials Conference*, Denver, June 2000.

5. "Carrier dynamics in self assembled InGaAs/GaAs quantum dots", (INVITED), S.Krishna, P. Bhattacharya, J. Urayama, T. Norris and P.J. McCann, *IEEE/LEOS Workshop on Semiconductor Lasers*, San Francisco, May 2000.
6. "Carrier dynamics in self-organized quantum dots and their applications to long-wavelength sources and detectors", (INVITED) P. Bhattacharya, S.Krishna, J.D. Phillips, P.J. McCann and K. Namjou, *XI<sup>th</sup> International Conference on Molecular Beam Epitaxy*, Beijing, China, September, 2000.
7. "A Room Temperature Unipolar Quantum Dot Intersubband Long-Wavelength Laser ( $\lambda=13$ ,  $\mu\text{m}$ )", S. Krishna, P. Bhattacharya, J. Singh, J. Urayama, T. B. Norris, P. J. McCann and K. Namjou, *IEEE LEOS Annual Meeting*, San Juan, Puerto Rico, November 2000.
8. "Long-Wavelength In(Ga)As/GaAs Quantum Dot Electroluminescent Devices", (INVITED) P. Bhattacharya, S. Krishna, J. Singh, P. J. McCann and K. Namjou, *Photonics West*, San Francisco, Jan 2001.

### Abstract:

While *interband* transitions in quantum dots have been extensively investigated for long wavelength (1.3  $\mu\text{m}$  and 1.55  $\mu\text{m}$ ) optical communications, *intersubband* transitions between the electronic levels formed in the conduction band of the quantum dot have not been widely researched. Since the intersubband energy spacing lies in the mid-infrared (3-20  $\mu\text{m}$ ) range, these transitions can be used for fabricating mid-infrared sources and detectors, which are in great need for applications such as space based infrared imaging, thermal imaging, night vision, thermography for electrical and mechanical fault detection, FTIR spectroscopy and environmental and chemical process monitoring. In this project, intersubband transitions in self-organized In(Ga)As/GaAs quantum dots were investigated and mid-infrared sources and detectors were fabricated. Spontaneous and stimulated emission centered at 13  $\mu\text{m}$ , was observed for the first time. We have also fabricated normal incidence quantum dot detectors ( $\lambda_p \sim 4\mu\text{m}$ ) with very low dark current ( $I_{\text{dark}} = 1.7 \text{ pA}$  for  $V_{\text{bias}} = 0.1 \text{ V}$ ,  $T=100\text{K}$ ), high detectivity ( $D^* = 3 \times 10^9 \text{ cmHz}^{1/2}/\text{W}$ ,  $T=100\text{K}$ ), and peak responsivity,  $R_p = 2 \text{ mA/W}$  ( $T=100\text{K}$ ) with a photoconductive gain,  $g = 18$  ( $V_b = 0.3\text{V}$ ,  $T=100\text{K}$ ) with the highest operating temperature (150K) for any normal incidence vertical quantum dot detector.